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Review

Modelling Agroforestry's Contributions to People—A Review of Available Models

Philipp Kraft [1,*], Ehsan Eyshi Rezaei [2], Lutz Breuer [1,3], Frank Ewert [2,4], André Große-Stoltenberg [1,3], Till Kleinebecker [1,3], Diana-Maria Seserman [2] and Claas Nendel [2,5]

1 iFZ Research Centre for Biosystems, Institute for Landscape Ecology and Resource Management, Justus Liebig University, Heinrich-Buff-Ring 26, 35392 Gießen, Germany; Lutz.Breuer@umwelt.uni-giessen.de (L.B.); andre.grosse-stoltenberg@umwelt.uni-giessen.de (A.G.-S.); Till.Kleinebecker@umwelt.uni-giessen.de (T.K.)
2 Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Straße 84, 15374 Müncheberg, Germany; EhsanEyshi.Rezaei@zalf.de (E.E.R.); frank.ewert@zalf.de (F.E.); seserman@zalf.de (D.-M.S.); Claas.Nendel@zalf.de (C.N.)
3 Centre for International Development and Environmental Research (ZEU), Justus Liebig University Giessen, Senckenbergstrasse 3, 35390 Giessen, Germany
4 Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Katzenburgweg 5, 53115 Bonn, Germany
5 Institute of Biochemistry and Biology, University of Potsdam, Am Mühlenberg 3, 14476 Potsdam, Germany
* Correspondence: philipp.kraft@umwelt.uni-giessen.de

Abstract: Climate change, increasing environmental pollution, continuous loss of biodiversity, and a growing human population with increasing food demand, threaten the functioning of agro-ecosystems and their contribution to people and society. Agroforestry systems promise a number of benefits to enhance nature's contributions to people. There are a wide range of agroforestry systems implemented representing different levels of establishment across the globe. This range and the long time periods for the establishment of these systems make empirical assessments of impacts on ecosystem functions difficult. In this study we investigate how simulation models can help to assess and predict the role of agroforestry in nature's contributions. The review of existing models to simulate agroforestry systems reveals that most models predict mainly biomass production and yield. Regulating ecosystem services are mostly considered as a means for the assessment of yield only. Generic agroecosystem models with agroforestry extensions provide a broader scope, but the interaction between trees and crops is often addressed in a simplistic way. The application of existing models for agroforestry systems is particularly hindered by issues related to code structure, licences or availability. Therefore, we call for a community effort to connect existing agroforestry models with ecosystem effect models towards an open-source, multi-effect agroforestry modelling framework.

Keywords: agroforestry; modelling; nature's contribution to people; ecosystem functions

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1. Introduction

Nature provides food, feed, energy and materials, as well as serving cultural needs, and regulates the earth system's functions. Termed "nature's contributions to people", or in short NCPs, they have been described by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) as a further development of the ecosystem service concept [1,2]. Annual cropping systems provide only a limited range of such contributions, their purpose lies in the provisioning of either food, feed, materials or energy. Building on a base of sole cropping, any addition of complexity to the cropping system is believed to increase its ecological value. Agroforestry systems, where annual crops are mixed with perennial trees in a single field at the same time, are at the high end of complexity. Such systems generally show a more diverse provisioning of NCP's [3], not only by the simultaneous production of different crops and materials, but also through an alteration in the regulation of ecosystem services [4–7]. Mixed cropping of annual crop plants with perennial trees allows farmers to gain a higher diversification of products within the same field and can result in a higher overall yield per area due to storey effects [8,9]. However, perennials limit mechanization, the flexibility of land management, and they increase the complexity of overall management [10]. Other priorities, including enhanced climate regulation, erosion control and/or increased landscape diversity, have boosted interest in agroforestry systems for stakeholders outside the farming sector, who view agroforestry as a tool to meet mitigation goals for climate change, increase habitats for insects and birds, or to make landscapes more attractive for tourists or recreationists.

Agroforestry systems are more diverse than conventional agricultural systems [11], as different tree species and crops multiply the possible combinations. In silvo-pastoral systems, tree crops are aligned with meadows suitable for pastorage, while silvo-arable systems combine tree crops with annual arable crops [12]. More complex combinations are also in use. The density of tree/annual crop interactions varies from alley cropping systems with wide row distances to wood pasture systems with an almost closed canopy. This diversity, which is specific to agroforestry, adds to the variability of conventional annual cropping systems, which is caused by climate, soil and topography. There have been only a limited number of established experimental sites where the effects of agroforestry on multiple NCP's have been studied. This limitation is especially apparent for temperate regions while more research has been conducted in the tropics. The number of experiments in temperate regions, however, is growing, with newly designed studies, but it will take several years to decades until the trees planted are mature enough to enable detailed investigations of the long-term system effects [13].

The time gap between the design of an experiment and the availability of its results makes the design and planning of an agroforestry system crucial. While it is easy to change a crop rotation that is based on annual plants, this is not the case for perennial systems and especially not for trees that might have a turn-around time of decades. Statistical approaches to predict optimized designs for different goals suffer from an incomplete knowledge base. Upscaling and design optimization are hindered by the small number of agroforestry sites, and the consequent low number of observations of system responses to interacting environmental and management factors [11]. However, policy makers who work at a regional, national and international scale need to know which effects are to be expected from large-scale promotion of agroforestry systems, before they design and implement their policies. While experiments are few, simulation models can be used to predict the effects of introducing agroforestry systems; several of those currently available have been reviewed by Lüdeling et al. [14].

The models can be roughly separated into three classes: (a) simplistic large-scale effect models, (b) simplified models with limited data requirements for agricultural extension and modelling landscape-scale effects, and (c) process-based research tools on the plot-to-field scale. In general, models of type (a) are built using informed hypotheses about agroforestry functioning and analogies with annual agro-ecosystems and forestry upscale effects to regional or even continental scale, such as the ESAT-A [15] indicator system, similar to the well-known InVEST system [16]. Simplified, data-sparse, process-oriented growth models, type (b), e.g., YieldSAFE [17] can be used by practitioners for agricultural extension services. Such models have been created to represent different designs of agroforestry systems with process complexity adjusted to publicly available data. Models of this complexity level can be used at a landscape scale without the need for specialist computation hardware. However, their simplicity limits their ability to predict effects that emerge from interdependencies of various ecological effects. In contrast, process-based models, type (c), in which the spatial configuration of species composition and the interaction between trees and annual crops is represented in detail, often benefit from a long development legacy in either agroecosystems or forestry, and include a well-tested body of algorithms. Their biophysical nature makes them transferable and these models have been successfully applied in agroforestry systems. However, the demand for input data, the prevailing lack of knowledge on the driving mechanisms of the competition or facilitation (tree-crop) for resources, and computational limitations, preclude detailed process models for regional applications (e.g., WaNuLCAS) [18]. One of the key features of process-oriented agroforestry models is the ability to simulate interactions between trees and crops in the same field, including the competition for light, water and nutrients, and changes in the microclimate [14]. General land-use models usually do not consider this interaction, even though they are developed to model both annual crop growth and perennial tree growth individually on different patches. However, applying process-based models on scales larger than a field requires large computational resources and detailed datasets for model calibration and testing, which is why simpler models are often preferred on larger scales. A particular strength of the process-based models then lies in their ability to investigate complex feed-back mechanisms in the represented system.

Especially for agroforestry systems, the contribution of system features, management and design, to NCPs is not fully understood [19]. Here, process-based models have great value for testing hypotheses, increasing system understanding, and informing on-field experimentation prior to establishment, through virtual experiments [20,21]. This is particularly relevant for agroforestry systems because of the long timeframes required for their establishment and their large number of designs. Once designed and parameterised, process-based models can create a space of possible agroforestry system responses to external variables, which can then be picked up by simpler models (emulators), meta-models, or form the basis of indicator systems for scaling to larger areas or over longer time spans, which is often required for policy support [22,23]. Figure 1 shows the conceptual relations and feedback between real agroforestry systems, agroforestry models and policymaking, highlighting the benefits of decision support by use of models.

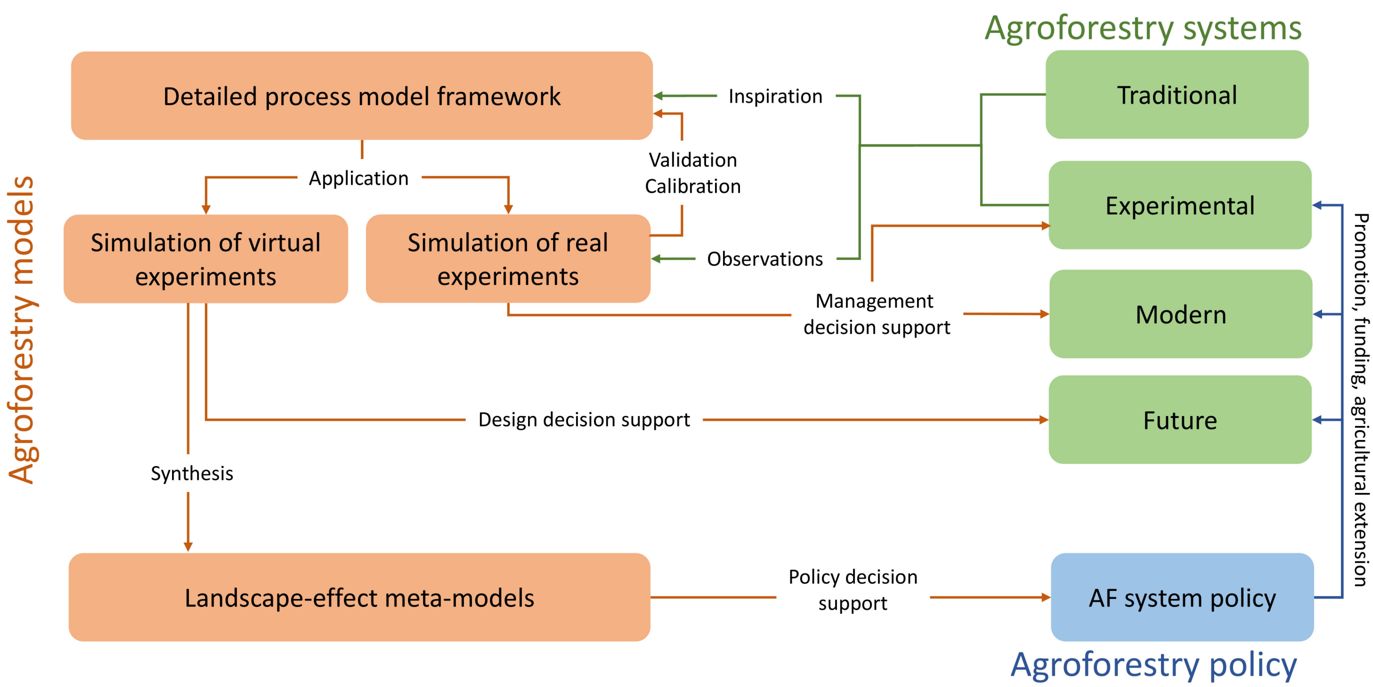

Figure 1. Relationships and feedbacks between established agroforestry systems, models and policy. Agroforestry systems are divided into traditional smallholder systems that have developed at local or regional scale over long timespans, experimental systems managed by research institutions, modern operative systems managed by farmers for production, and not yet established future systems in a model-guided design phase towards optimized contributions to people.

In this framework, detailed process-oriented models are calibrated and validated against existing experiments. These models can be used to quantify and optimize nature's contributions to people (NCP) in existing agroforestry systems, according to the needs of the stakeholders. With virtual experiments, new designs and layouts of agroforestry systems can be tested prior to establishment with respect to the productivity and ecosystem services (ES) rendered by such systems. In virtual landscapes, they can be used to identify gradients of agroforestry system design and create indicator systems and meta-models for large-scale application.

Objective

In this study, we reviewed available biophysical agroforestry models for their ability to assess relevant ecosystem services, using the concept of nature's contributions to people, as suggested by Fagerholm et al. 2016 [19]. We identified structural, technical and legal problems for cooperative model development to solve problems associated with the current state of agroforestry models.

Biophysical models do not assess NCP's directly, but they predict effects on ecosystem properties such as wind speed, carbon storage or groundwater recharge. Section 2 compiles the ecosystem properties (or model output variables) relevant for the provision of NCP's and stakeholders based on a review of the current literature. Section 2 also introduces the groups of NCPs to be used in Section 3.

Section 3 provides an overview of current biophysical agroforestry models and lists which NCP relevant system properties are covered by their model outputs. The model outputs from Section 2 covered by the models in this review are shown in Table A1, Appendix A.

Section 4 discusses the structural, technical and legal properties of agroforestry models, in order to investigate their potential to be extended by the scientific community to cover a broader set of NCP-related model outputs and processes.

2. Agroforestry Ecosystem Properties Contributing to People

2.1. Groups of Nature's Contributions to People (NCP)

Agroforestry's contributions to people are different as compared to landscapes in which patches used for agriculture and forestry are spatially separated. Process-based models calculate states and fluxes of the biophysical properties of nature. These biophysical properties of agroforestry systems need then to be translated to NCPs. We demonstrate this using the system of 18 NCPs as presented by Díaz et al. [1]. Their approach, however, is partially redundant in terms of ecosystem properties: e.g., provisioning of habitats for various animals and plants (NCP 1) mostly includes the ability to provide habitats for seed and pollen dispersing animals (NCP 2), although the type of contribution differs. To overcome these redundancies, in this paper, we propose links between agroforestry system properties and NCP groups (Table 1). We identified NCPs related to biodiversity (NCP 1, 2, 10, and 14), air quality (NCP 3), climate (NCP 4), water percolation (NCP 6–8), surface protection (NCP 8–9), production (NCP 11–13) and the group of socio-cultural NCPs (NCP 15–17). Ocean acidification (NCP 5) is only indirectly related to agroforestry and was excluded from this study. Nature contributes to people by enabling opportunities, to benefit humanity in ways to be discovered (NCP 18). As models can only be based on already existing knowledge, NCP 18 is not part of this study, although it is perceived as one of the major benefits of agroforestry [24].

2.2. Linking NCP Groups with Agroforestry System Properties

2.2.1. Biodiversity

Agroforestry increases the compositional heterogeneity (i.e., the number of different habitat types, NCP 1), as well as habitat connectivity (i.e., higher field border density, NCP 2) which are both primary factors benefitting biodiversity at the landscape scale [6]. High edge density and increased connectivity in agricultural landscapes were also shown to promote functional biodiversity of arthropod pest antagonists, which in turn enhance yields (NCP 10) [25]. Aside from their habitat function, supporting a multitude of different plant and animal species, agroforestry systems can also serve as an important gene reservoir, such as for old varieties of fruit trees (NCP 14) [26].

Table 1. Groups of nature's contributions to people, summarized from Table A1 in Díaz et al. (2018). The types are regulating (R), material (M), cultural (C), and options (O).

Group	NCP	Type	NCP-Name	Exemplary System Property
Biodiversity	1	R	Habitat	Animal diversity Plant diversity Landscape diversity
	2	R	Seed/pollen dispersal	
	10	R	Pest regulation	
	14	M	Biotechnology	
Air quality	3	R	Air quality	Pollution filtering, dust prevention
Climate	4	R	Climate regulation	CO_2 emission, C-sequestration, Surface cooling, Evapotranspiration
	5	R	Ocean acidification	
Water	6	R	Water quantity	GW recharge N/P-load, water supply, N supply
	7	R	Water quality	
Surface protection	8	R	Soil protection	Soil functioning, vegetation cover, wind/water erosion
	9	R	Hazard regulation	
Production	11	M	Energy	Woody biomass, Crop biomass, Fruit biomass, timber biomass
	12	M	Food & feed	
	13	M	Materials	
Culture	15	C	Learning & inspiration	Landscape character/beauty Culture heritage
	16	C	Experience	
	17	C	Identities	
	18	O	Options	Not part of this study

2.2.2. Air Quality

Aerosol deposition increases due to the increased surface roughness, which reduces the velocity of air flows [27]. This creates a sink for air pollutants. Shelter belts can reduce the odour diffusion of livestock production and manure application [28], depending on the density, geometry and the shape of the selected tree species' leaves. Urban trees filter pollutants in a similar manner in cities [29]. Due to the decreased wind speed at the crop level, alley-cropping systems can significantly reduce drift emissions during the application of fertilizer and pesticides [30]. Fine, respirable mineral dust, originating from wind erosion, is another threat to air quality, which agroforestry systems have the potential to mitigate. The system property regulating air quality is the altered wind field, with decreased velocity and enhanced turbulence of the air flow.

2.2.3. Climate Regulation

Agroforestry systems can enhance the resilience of agro-ecosystems towards climate change [31]. Important biophysical vegetation-atmosphere interactions include energy exchange through latent heat, radiation transfer, storage of carbon below and above ground, and the emissions of greenhouse gasses (NCP 4, NCP 5). For example, agroforestry can reduce the net loss in long-wave radiation from plant surfaces and protect plants from radiation frosts locally [32], alleviate drought stress of the crop [33,34], and alter the temperature, with positive and negative effects on the crop depending on the growth stage [33]. Agroforestry can further alter surface roughness and thus airflows [35], with potential effects on plant productivity through the reduction of wind speed [33,36], and reduce evapotranspiration of the crop [37] with potential effects of the tree age [38].

Agroforestry is also capable of directly mitigating climate change. Several studies have reported on the positive effects on C storage in such systems [4,39,40]. Much less information has been published on the role of agroforestry systems and trace gas emissions. Reduced CO_2 and N_2O emissions and increased CH_4 sinks have been reported for the humid tropics [41]. However, the effects of agroforestry for other climates are less clear from reported reduced emissions [42] but also from higher emissions during freeze-thaw cycles [43].

2.2.4. Water Regulation

Soils are important filter systems for rainwater to percolate through. Nutrients and pollutants undergo a complex interaction with soil minerals and biota, and purified water adds to groundwater resources from which drinking water is then retrieved [44]. In contrast to forests with minimal percolation beyond the rooting zone [45,46], croplands and grasslands play an important role in groundwater replenishment. However, as they are often heavily fertilized to ensure production, groundwater quality is at risk. Adding trees to a site that is otherwise cropped with annual plants adds another rain interceptor [47] and water consumer, whose roots may eventually grow underneath the annuals [48,49]. This increases the water and nutrient use efficiency of the system [50], but leaves even less water for deep percolation and groundwater recharge. Reducing the radiation input through shading improves the growth condition for the annuals in most circumstances, so that reduced radiation input is compensated for by less stress through high temperatures and slower development [51,52], despite higher night temperatures [53]. A better growing crop, however, consumes more water and nutrients. If wide agroforestry architectures are employed, deep percolation of water and, consequently, leaching of nutrients occurs in the centre rows between tree lines with higher probability, compared to the field edge in the vicinity of the tree row [54]. In some circumstances, trees increase the water percolation, which leads to an optimum tree share that balances positive and negative effects on deep percolation [55].

2.2.5. Surface Protection

The long-term development of soils is crucial as they are a natural resource for the provisioning of most NCPs as a habitat for animals and plants, (NCP 1, 2, 10), regulation of water quality and quantity (NCP 6, 7), and as a basis for land production (NCP 11–13). The effect of wind erosion on air quality has already been addressed in Section 2.2.2. The physical protection of the on-site surface is therefore a future contribution of nature to people (NCP 8). The tree canopy protects the surface from the destructive kinetic energy of rain drops. Tree roots reduce soil disturbance, stabilize aggregates, develop preferential flow path in soils, and lead to higher infiltration capacities [56]. This can, depending on the agroforestry system design, slow down surface runoff by increasing the surface roughness. Higher surface water retention in the field means less flash floods and sediment deposition off-site, protecting surrounding dwellings from hazards (NCP 9). Increasing the share of agroforestry systems in a watershed can therefore change the runoff characteristics of a landscape. Relevant properties include the surface roughness, the physical protection of the soil from splash and detachment, the infiltration capacity, and changes in micro-topography.

2.2.6. Production

Tree and crop combinations in agroforestry systems provide a wide range of products (NCP 11–13) to people, which contribute to food security (food and feed), income (wood and timber), and specific products (rubber, coffee, tea, and cacao) [57–59]. The ecological nature of the interactions between tree and crop components in agroforestry systems can lead to improvements in overall product quantity without suppressing the benefits of other ecosystem services to people [60]. Agroforestry models can address the crop-related NCPs by simulation of crop biomass and grain yield (NCP12) in reasonable detail; however, most of these models have failed to simulate tree growth processes (NCP11) and by-products such as rubber and fruits (NCP13) [14].

2.2.7. Socio Cultural Contributions

Agroforestry systems have been a commonly applied land-use system across Europe before mechanization and mineral fertilizer application changed agricultural production [61]. As parts of a lost landscape of the past, Elbakidze et al. [24] showed, for four Baltic countries, that the benefits of agroforestry are predominantly perceived as socio-cultural contributions. However, modelling agroforestry systems as places to support identities, for learning, and to generate physical and psychological experiences, is extremely dependent on the location and historic uses of agroforestry. There is no distinct, measurable property of agroforestry systems that can be used as a global indicator of socio-cultural contributions. By the diversification of agricultural landscapes and by increasing biodiversity, agroforestry can support human well-being and people's identification with their home region [62]. For regional studies, additional indicators producible by models may exist, like the abundance of free-standing oaks in central Sweden [63] or apple trees in central Germany [26].

2.3. Stakeholders for Modelling NCPs of Agroforestry Systems

Different stakeholders expect predictions of different NCPs (ref. Table 1) and knowledge generation at various scales from agroforestry models. We classified the interest groups of agroforestry models into farmers, agribusiness (including advisors, companies and insurance providers), researchers, non-governmental organizations (NGOs), and policymakers.

Farmers are generally interested in site-specific simulations providing crop yield, fruit, timber, and wood production (NCP 11–13) [64]. Furthermore, near-real-time predictions of soil variables covering the spatial heterogeneity of the field are in high demand by farmers, as they promise valuable information towards improved tactical management [65]. Agroforestry models suitable for farmers should therefore cover the effect of various management practices for decision support from field-to-farm scale [66], including biotic (biodiversity, particularly NCP 2 and NCP 10) and abiotic stresses (e.g., water and nutrient deficiency, heat; NCP 4, NCP 6) affecting production [67]. In response to policy regulations, they need to consider the environmental impact of their activities on air (NPC 3), water (NCP 6), and soil (NCP 8) quality. Many farmers are an essential part of a tradition-oriented rural society with strong cultural aspects (NPC 16 and NCP 17).

Agribusiness companies are mainly concerned with employing models for simulating crop yield or wood/fruit production (NCP 11–13), depending on their service portfolio for field and farm scale [68]. Agroforestry models used by agribusiness companies should ideally focus on specific processes or field management options in detail [69] particularly with respect to pest and disease control (NCP 10). For instance, fertilizer or pesticide producers are interested in the responses of crops and trees to the application of their products. They also require the models to trace the impact of chemicals on water quality (NCP 7) and soil health (NCP 8). Insurance companies are interested in farm to regional-scale simulations that relate production (NCP 11–13) to extreme events (e.g., heavy rain/hail, drought and frost) covered by NCP 4 and NCP 9. They seek to separate the effects of mismanagement from meteorological variables, which are beyond farmers' control. In addition, analyses of inter-annual yield variability and spatial yield maps are target outcomes for such companies. The product market is interested in reliable predictions of the upcoming harvest to adjust logistics and sales. Agribusiness is also sometimes interested in developing their own models but their intention for doing so is purely market oriented.

In contrast, researchers develop models to answer specific scientific questions and gain process understanding (NCP 15). They are interested in simulation of processes, effects and feedback loops across different spatial and temporal scales, to disentangle the complex interactions among management, environments, and plants. A perfect model for researchers simulates various products such as crop yield, fruit, timber, and wood (NCP 11–13) and impacts on the regulation of NCPs (1–10) depending on the research question [70]. Researchers need modelling platforms with a nested structure that simulates different processes with various degrees of complexity for each process depending on the application scale, considering the available observed data for model calibration and validation. Researchers' expectations from a model can cover all NCPs.

Stemming from a desire to help people to both receive and deliver sufficient, safe and nutritious food, feed and materials, NGOs target most of the NCPs identified in this study. From providing educational resources to consulting other stakeholders regarding agroforestry practices, NGOs support the continuous development and improvement of such systems through information campaigns and on-site projects [71]. For this, NGOs sometimes use models or model results to revise their goals and evaluate their projects, in a similar way to policy-making in governmental organizations.

Lastly, policymakers are one of the main stakeholders using the output of agroforestry models with interested in a regional or national context [72], as advised by their supporting agencies. Since high-resolution model inputs are often not available at the regional scale, models with a simple structure are preferred to those that require detailed information for model calibration [73]. Such models should be able to project strategies for adaptation to and mitigation of climate change impacts and weather extremes (NCP 4, NCP 5, NCP 9). Other environmental impacts of concern are impacts on air (e.g., NH_3 emissions or particulate matter exposure PM2.5; NCP 3) and water quality (NCP 7). More recently, the impact of agricultural activity on biodiversity, especially insect diversity, has gained momentum and has led to interest in NCP 1 and NPC 2. For future planning and exploration of policy options, policymakers might be interested in coupling such agroforestry growth models with economic models. Given that political decisions are responsible for landscape planning, NCP 15–17 should be addressed by specific models as well.

3. Assessing Nature's Contribution to People with Existing Models

3.1. Existing Agroforestry Models

Lüdeling et al. [14] described and compared eight different agroforestry models selected for their ability to directly model the interaction between annual crops and trees. We have extended this list to a total of 13 models, to include all biophysical agroforestry models we identified in the peer-reviewed literature addressing the mixed cultivation of annual crops/grassland and trees (Table 2). The list of models includes detailed generic growth models, encompassing different tree species and crops (Hi-sAFe, WaNuLCAS, SCUAF, APSIM, and EPIC). Hi-sAFe, WaNuLCAS and SCUAF have been designed for agroforestry systems specifically, while APSIM and EPIC are general plant growth models that have later been adapted to simulate agroforestry systems. APSIM is a full-bodied mechanistic simulation model that describes agroforestry systems in a high level of detail. In the case of EPIC, Easterling et al. [33] varied the weather input file to account for windbreaks and shading. Another family of models includes highly specialized process models built for specific cropping systems: SBELTS (soy with shelterbelts), WIMISIA (millet with wind breaks), COMP8 (pine and grassland) and DynACof (coffee under shade trees). The HyPAR model connects a generic tropical broadleaf tree growth model with a specific sorghum crop model (PARCH). A similar approach exists in combination with a cassava model (GUMCAS [74]) with the name HyCAS [75]. ESAT-A is an indicator system for agroforestry effects without explicit temporal dynamics.

Table 2. Agroforestry models considered in this study.

Model	Reference	Type of Model	Spatial Representation
Hi-sAFe	[76]	Detailed generic process model	3D structure
WaNuLCAS	[18]	Detailed generic process model	2D hillslope
SCUAF	[77]	Detailed generic process model	unclear
APSIM	[67,78,79]	Detailed multi-crop process model	2.5D area
EPIC for AF	[33]	Detailed generic conceptual model	2.5D area
SBELTS	[80]	Soy growth model with shelterbelt effects	1D horizontal
WIMISIA	[81]	Millet growth model with wind break effects	2D vertical plane
COMP8	[82]	Competition between Pines and surface cover vegetation (weeds, crops)	2D vertical plane
DynACof	[83]	Detailed process model for coffee under shade trees	Meta model from 3D canopy shading model
HyPAR	[84]	Conceptual model for sorghum with tropical hybrid broadleaf trees	Field level
Yield-sAFe	[17]	Generic conceptual model	Field level
ICBM/N	[85]	Water balance model	Field level
ESAT-A	[15]	Indicator system	Landscape level

3.2. Assessment of NCP Relevant Ecosystem Properties by Existing Agroforestry Models

Each of the listed models has been developed to answer different research questions. It was not the main purpose of these models to capture nature's contributions to people in general, rather models have mainly been developed to capture the productivity response of agroforestry systems to environmental and management drivers. An exception is the indicator system ESAT-A, which has been developed to assess the impact of agroforestry on ecosystem services for large-scale applications. However, it does not consider feedback loops and system dynamics. We show in the following sections which of the available models assess the relevant ecosystem properties from Section 2.

3.2.1. Biodiversity

Biodiversity plays a subordinate role in agroforestry research [19]. Agroforestry has been shown to particularly improve regulating services including biodiversity [86] by increasing both the number of different habitats and the edge density.

With a focus on production, recent agroforestry models do not contain procedures to characterize habitats for animals, unplanned successional plants, or microbial diversity, although feedbacks between the population density of seed dispersing insects and yields exist. Only ESAT-A uses an indicator to estimate effects on plant biodiversity by introducing agroforestry, but in a very simplified manner. Although not directly incorporating biodiversity as a driver for outcomes such as crop yield, the Hi-sAFe model uses competition and facilitation, which are important mechanisms explaining positive biodiversity-productivity relationships in biodiversity ecosystem functioning research [76]. Independent from the agroforestry models in this review, Shachak et al. [87] provided a theoretical framework for studying the environmental impacts of woody plants to understand their effects on biodiversity. Woody biomass patches differ from the surrounding in variables such as shade, water, and litter regimes. The contrast between woody patches and their surroundings affects organism assemblages and biodiversity. Prevedello et al. [88] presented a simple, synthetic, individual-based model that generates realistic patterns of species richness and density as a function of landscape structure. Sybertz et al. [89] developed a simple model to predict bird and plant richness in farmland; bird richness was able to be successfully modelled. However, biodiversity models of any scale are often site-specific and can have a narrow scope of application.

3.2.2. Air Quality

No model subject to this review includes a detailed mixing routine to simulate the exchange of aerosols between the free atmosphere and the surface. SBELTS, WIMISIA and EPIC include routines to model vertical wind profiles for agroforestry systems, which can be used to extend the models with emission/deposition models. Explicit wind erosion models are also not included in the agroforestry models. Only the EPIC/APEX modelling family, a land use modelling package often applied for agroforestry systems, contains an empirical risk assessment formulation for wind erosion impact. The number of available wind erosion models is generally limited, as reported in a review by Jarrah et al. [90]. Large scale applications are dominated by empirical simplified models for wind erosion like the WEQ/RWEQ [91] model family with an approach comparable to the universal soil loss equation (USLE) [92] for soil loss by water; the EPIC/APEX model family uses a similar approach. Differences in design between agroforestry systems, like row distance, tree geometry and spacing can only be captured by an integrated factor, which is yet to be defined by the scientific community. The WEPS model is predominantly used in process-based wind erosion modelling studies [90]. It can simulate the spatial explicit impact of tree patterns [93] and provides a time-continuous modelling of the top soil moisture.

3.2.3. Climate Regulation

Changes in biophysical feedbacks between vegetation cover and atmosphere albedo, long-wave-radiation, evapotranspiration, surface roughness and cloud formation can have both positive and negative NCP-related effects [1]. In current agroforestry models, such parameters are rather poorly covered. This contrasts with their importance in physical models to assess the potential cooling effects of afforestation [94]. They are highly relevant in terms of NCPs, as afforestation (e.g., for carbon sequestration) changes the land surface reflectance, which affects land surface temperature positively and negatively, depending on climate zone and latitude [94]. Furthermore, the offset between the potential warming effects of afforestation and carbon storage has a temporal dimension [95]. While cloud formation is only partly considered in one current agroforestry model (APSIM), albedo and long-wave radiation are covered in two recent models (APSIM, DynACof). Solar radiation is more commonly used as an input parameter that defines plant growth (e.g., EPIC), rather than as an output variable. Similarly, surface roughness is only computed in one model (SBELTS, "roughness height"). In contrast, evapotranspiration can be retrieved from most existing models, sometimes even separately for soil evaporation and plant transpiration (WaNuLCAS). Therefore, we identify a need to represent the biophysical feedbacks between vegetation cover and atmosphere both spatially and temporally in future agroforestry models to explore potential cooling or warming effects of systems, particularly regarding interactions with other NCPs related to carbon sequestration.

The soil carbon cycle is poorly represented in most of the agroforestry systems models (Table A1). While more than half of the models simulate at least some aspects of plant-based carbon storage (including roots) only the comprehensive modelling platforms APSIM and EPIC can simulate the complex C and N turnover belowground, and their effect on soil carbon storage. This is astonishing, to say the least, when one takes into account that agroforestry systems are often primarily implemented to increase carbon storage in terrestrial ecosystems [39,40]. Emphasis is put on aboveground carbon storage, neglecting the fact that soils can store vast amounts of carbon. The YieldSAFE model has been extended with soil carbon storage routines [96] to address this gap.

Equivalently important are greenhouse gas emissions and how they are influenced by agroforestry system design and their management [41]. Surprisingly, we found no study where greenhouse gas emissions have been quantified in model-based assessments for agroforestry systems. However, APSIM and EPIC are generally capable of simulating greenhouse gas emissions. For the further consideration of greenhouse emissions, process-based models such as LandscapeDNDC [97] or DAYCENT [98] could be considered in agroforestry model systems.

3.2.4. Water Regulation

Water and nutrient dynamics are often central when agroforestry is suggested as an option to increase nature's contributions to people. The main assumptions on micro-climate regulation through agroforestry have direct consequences for plant growth and subsequent water and nutrient consumption and loss. The different hypotheses on the benefits of additional trees in croplands have been partly tested in field experiments, but the interactions of plant growth, water and nutrient dynamics are so diverse that mechanistic simulation models need to be employed to fully disentangle the individual contributions of the different factors involved. From a human perspective, the main concern lies with the effects of agroforestry on groundwater replenishment, groundwater quality, and water and nutrient supply to plants for biomass growth and yield formation. Among the existing models, many do simulate drainage and nitrate leaching in a mechanistic way (e.g., HyPAR, WIMISIA). However, nutrient dynamics or, specifically, the release of nutrients from soil organic matter turnover is often not considered. DynACof 3D models contribute here with their ability to separate different zones of root distribution across an agroforestry site. This allows testing of whether, and at which distance, the presence of trees affects the drainage of water and subsequent leaching of nutrients. Such 'leaky' zones could be simulated as a major contributor to nutrient losses underneath agroforestry systems, but also for potential groundwater replenishment.

The water consumption of crops and trees influences the soil water budget. A full consideration should include the interception of rain in different canopy storeys, the spatial redistribution of rain through stem flow and canopy drip, and a plausible representation of crop and tree transpiration and water uptake from soil. Here, agroforestry models benefit from existing agro-ecosystem models, from which some have borrowed modules for soil water and nutrient dynamics (e.g., SBELTS, APSIM). However, a 3D structure would be required to represent the spatial pattern and identify hotspots of drainage.

The resulting soil moisture, in turn, has effects on soil organic matter turnover, for which an optimum soil moisture exists. The resulting nutrient release adds to the nutrient availability for plant uptake, but also for losses. In the case of N, both nitrate (leaching) and nitrous oxide (gaseous emissions) formation are affected; in the case of C, it is the building up of recalcitrant soil C stocks and the emission of CO_2. This feedback is included in the mechanistic agro-ecosystem models. Phosphorus release and availability is only considered in a few models (e.g., WaNuLCAS, Hi-sAFe, APSIM), with various levels of complexity. Feedback to erosion, an important pathway for P losses, is not considered in any of the agroforestry models reviewed.

The Hi-sAFe model is potentially able to address all the above-mentioned feedback loops, and has done so with many of them already [51]. What is still missing is the feedback between soil moisture and soil organic matter mineralization/plant N uptake, and the question of whether agroforestry would really reduce N leaching or would just make zoning of N fertilizer demand even more complicated, with undesired effects on N leaching. Some of the agroforestry models do not consider deep percolation of water and nutrients as an output, as their focus lies solely on the feedback between soil moisture and plant growth (e.g., Yield-sAFe), or on the dynamics of soil C stocks (ICBM/N).

3.2.5. Surface Protection

Water erosion is integrated into SCUAF, EPIC/APEX and APSIM using the USLE model family. The USLE [92] is an overlay of empirically derived factors describing the erosivity of rainfall events, the erodibility of the soil, topography, soil cover by crops, and factors affecting the effectiveness of soil protection measures, e.g., contour ploughing. In an application study of the Farm-sAFe model, the soil erosion protection of agroforestry was calculated by factoring the tree canopies into the soil cover factor [99]. Process-oriented modelling of soil erosion is deliberately left out of the agroforestry process model Hi-sAFe [76]. The WaNuLCAS model contains a mechanistic approach to water erosion running, as does the rest of the model, on a daily time step. A comparison of a calibrated WaNuLCAS model with the erosion model WEPP [100] for an agroforestry system in Thailand showed a strong overestimation of the surface runoff [101]. The rangeland hydrology and erosion model (RHEM) [102] is based on WEPP, but has been extended with parameters for a better capture of woody patches, but this model package omits routines for plant growth in the herbal/crop and tree layer and is therefore not a subject of this study.

The integrated modelling systems available do not directly capture roughness and infiltration effects. However, at least WaNuLCAS can be setup with a predefined macro pore regime. Plant growth and the presence of trees changes the surface roughness. A modelling study for wide tree strips in Australia showed a strong effect on the soil moisture distribution by changes in surface roughness and infiltration capacity [103], which is missing in available integrated crop-tree interaction models.

3.2.6. Production

The primary motive behind developing and applying most agroforestry models is to simulate crop and tree products under various environmental conditions and management practices [14]. The main products of the crop component simulated are above-ground biomass and marketable yield [104]. The tree component generally simulates wood, timber, and in rare cases, fruit yield [104]. The simulation of fruit yield is complicated since the fruit quality properties (such as size, shape, colour, and water content) are the more critical variables for marketability in most cases, and not the fruit quantity, where approaches that are more generic can be employed. Most of the agroforestry models use the light use efficacy concept [105] for biomass accumulation and partitioning coefficients to distribute the assimilates across the organs in both crop and tree components [14]. However, a few models employ a daily net photosynthesis concept to simulate above-ground biomass [84]. Water and N deficiencies are the only biomass and yield-limiting factors considered by agroforestry models, generally represented by using simple reduction factors, while P deficiency is usually missing. Nevertheless, Hi-sAFe simulates water and nitrogen stress using a process-based approach that affects leaf area index, light use efficiency, and allometric coefficients. Agroforestry models mainly consider the competition for light as the primary driver of direct interactions between crop and tree components [106]. On the other hand, the direct competition for water and nitrogen are not adequately represented due to the lack of data for calibration and a knowledge gap in process understanding. A few models partly reproduce the below-ground competition between species, considering the difference in transpiration demand, available water, and N in the overlapping root zone, the difference in potential uptake rate of roots, relative root length density, and pre-defined resource distribution among crops and trees (Hi-sAFe, Yield-sAFe, WaNuLCAS).

There is a trade-off between the numbers of processes considered by models and the parameterisation efforts needed to simulate yield and tree products [104]. The 3-D and 2-D models which consider impacts of a broad range of management options, including thinning, branch/root pruning, fertilization, irrigation, mulching, etc., require more intensive parametrization efforts especially with parameters that are mainly available at field scale, making upscaling a challenge for the users [14]. Another shortcoming of the current agroforestry models, being species-specific, is the lack of generic crop and tree components in the modelling platforms, limiting their application across environments.

3.2.7. Socio Cultural Contributions

As discussed in Section 2.2.7, there exists no global indicator or ecosystem property, with a universal translation into social cultural contributions. Consequently, none of the model descriptions mentions usage of the model to address the socio-cultural contributions of agroforestry systems to people.

3.3. Summarizing the Models Abilities to Assess NCP Related Ecosystem Properties

Table A1 list all of the models considered in this review and their ability to model the ecosystem properties connected with specific NCPs as structured by Díaz et al. [1]. Every ecosystem property that is fully assessed by a model is marked with 100%, partial coverage with 50%. Table 3 summarizes this information with the mean values of each model for the NCP groups.

Process models for agroforestry systems have mainly been developed to optimize productivity of the systems, which is therefore the focus for all models. Generic modelling of multiple crop and tree species, including wood and fruit production, is almost not possible (Table A1). Due to the role of water and nutrient supply in productivity, water quantity and quality regulation is also a core feature of the available models. Impacts on the biodiversity-related contribution to people are not a subject for the existing models, except for the indicator system ESAT-A, which offers at least some indicators for plant diversity. Other groups of NCPs are also covered by only a few models, like air quality and surface protection, often by rather large-scale conceptual models, and not by process-oriented models. Properties for climate regulation effects are only scarcely modelled, with the mechanistic crop growth models APSIM and EPIC as exceptions.

None of the models produces output to assess all of nature's contributions to people. To cover a broader range, existing process models need to be enhanced or coupled with adequate routines from other models, if possible. Such a framework of integrated models and routines from different disciplines needs to overcome technical, conceptual and legal barriers to become possible.

Table 3. Average coverage value for the models to assess NCP-related ecosystem properties. Shading emphasizes higher coverages. The coverage percentage is derived from Table A1.

	Hi-sAFe	WaNuLCAS	SCUAF	APSIM	EPIC	SBELTS	WIMISA	COMP8	DynACof	Hypar	Yield-SAFE	ICBM/N	ESAT-A
Biodiversity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	33%
Air quality	0%	0%	0%	33%	67%	33%	33%	0%	0%	0%	0%	0%	33%
Climate	20%	15%	5%	90%	45%	20%	15%	0%	40%	15%	15%	0%	5%
Water	100%	100%	40%	100%	80%	40%	20%	100%	40%	100%	100%	0%	60%
Surface protection	25%	63%	50%	50%	50%	0%	25%	0%	0%	25%	50%	25%	50%
Productivity	75%	75%	63%	50%	50%	38%	38%	0%	50%	50%	75%	0%	0%

4. Towards a Multi-Effect Modelling Framework for Agroforestry

Section 3 shows that the state of modelling agroforestry systems with regard to NCP's is still lacking the tools to assess a broad and relevant set of ecosystem services [19]. The complexity of agroforestry systems results in complex models. Extending agroforestry models to cover all NCPs requires more work than a single group of experts can deliver in the scope of a project. Instead of solving all links between NCPs and management at once, we would like to propose building step-by-step on existing models from within and from outside the agroforestry modelling community to form a multi-effect modelling framework. How well existing models fit into a community led framework depends on technical, conceptual and legal issues relating to the models' source code. Such a framework will be complex to build and use and would result in a research tool and not necessarily an operational tool directly useable by modelling stakeholders outside of the research community.

4.1. Technical and Conceptual Requirements

Lüdeling et al. [14] have already sketched a "way forward" for agroforestry model development, highlighting some features for the future of agroforestry modelling including flexibility through interoperability, model simplicity, and model longevity. These requirements are even more necessary for a multi-effect modelling framework that enables the simultaneous assessment of various regulating NCPs. We expand on this here with more features, incorporating the earlier ideas of Buytaert et al. [107] on modularity, portability and accessibility.

4.1.1. Accessibility and Model Longevity

Model source code that is widely accessible has a higher chance of being taken up by others and developed further, even if the original developers subsequently lost their interest or means. Model code becomes accessible if it is: (i) published with a code license approved by the free software community [107], (ii) well-structured and documented, and (iii) written in an appropriate and widely used programming language. If any of these aspects is missing, the model code cannot easily be passed from one developer or institution to another, with a view to reducing the risk that society might lose model applications at the end of a specific project or initiative, as described by Burgess et al. [108]. Accessible source code is the prime requisite of model properties for further development. We use level indicators to describe a gradual shift from no accessibility at all to full accessibility, as follows: (0) no published information concerning the model implementation, (1) mentioning of a few implementation details (e.g., platform), but no information about code access, (2) published promise on code access on request, unclear terms and licenses expressed, (3) published promise on code access on request, proprietary license and/or special legal requirements on usage, (4) download of source code from public repository with proprietary license, (5) download of source from repository with a free license approved by the Free Software Foundation. All accessibility levels below (5) are not sufficient to integrate a model code into a community framework.

4.1.2. Portability

Portability describes the potential to run a model across a wide range of hard- and software platforms. It is important for users interested in running single scenarios and for developers working on specific model mechanics to run a model code on a normal PC. These users can also profit from a graphic user interface. For large-scale applications, statistical parameter optimization and uncertainty assessment, the same model code should be run massively parallelised on a high-performance computing cluster using different operating systems and hardware components. Graphical interfaces bound into the model code can prohibit these kinds of applications. Programming languages lacking support across operating systems or depending on expensive runtimes pose another problem for portable model frameworks.

4.1.3. Interoperability, Modularity and Simplicity

The term flexibility is mainly used by Lüdeling et al. [14] to describe the possibility to interface agroforestry models in a broader framework; we call it interoperability here. A flexible agroforestry model can be used as a module to be interfaced with other models like economic or catchment hydrology models, depending on the stakeholder's needs. Interoperability addresses the environment of the model.

Modularity, as required by Buytaert et al. [107] for hydrologic models, refers to the internal structure. Clark et al. [109] describe environmental models as a network of interacting hypotheses and assumptions and recommends that models are modifiable at the level of individual processes so that these assumptions can be tested individually. Such modular model kits are now available in hydrology, such as SuperFLEX [110] or CMF [111], which can be used to construct new models. Models for plant growth and soil chemistry are usually more complex. Modular approaches tend to refer to the replacement of complete sub-models describing a compartment. For example, in the biogeochemical models LandscapeDNDC [97], ExpertN [112] or SIMPLACE [113], different models are available for plant growth, biogeochemical processes in soil solution, and transport by water. However, the need for re-parameterisation of newly configured models remains a challenge.

The term simplicity, as used in Lüdeling et al. [14], means that a model should have a balanced complexity. However, the target complexity in each domain depends on the research question and on the NCP relevant for the stakeholders. The ability to change model components in a modular modelling framework, allows for the adjustment of model complexity with regard to the research question; hence modularity is also a tool to keep model simplicity balanced in an evolving modelling framework.

However, coupling existing sub-models to compose a flexible and modular super-model is still challenging, even if the models have been developed with the previously stated goals in mind. From our experience, major technical roadblocks for model integration include missing portable interfaces to internal states, boundary conditions and fluxes, incompatible spatial and temporal resolution and scope, incompatible licenses of the source code, and missing documentation at the implementation level. Interfacing different models creates an additional challenge: most environmental models have been validated for their predicted lumped effects and not at the process level. Combining processes from previously validated models does not automatically create a new valid model. The newly composed model needs to be validated against experimental observations.

4.2. Conceptual and Technical Issues of the Existing Agroforestry Models

Modelling research articles often omit technical and conceptual details, especially earlier articles. The availability of source code, or even executables, is not reported for most of the reviewed models. There is no mention of the source code availability, the programming language, or modelling platform used, for SCUAF, SBELTS, HyPAR, WIMISIA, ICBM/N, COMP8 and ESAT-A (accessibility level 0). While the mathematical model-equations can be reprogrammed in a new approach, code reuse for interoperability is not possible. Re-implementing the models for integration into a larger framework is demanding and error prone or not possible at all, if the original implementation cannot be used for guidance and verification. ICBM/N or its basis ICBM [114] (SAS and Microsoft Excel, respectively) was originally available online but the links for download in the references are no longer active. As a spreadsheet application, this model did not provide defined interfaces, modularity, or portability (accessibility level 1).

The process-based Yield-sAFe model has been implemented initially in Matlab and later as an Excel spreadsheet applications [17]. The Matlab version is not publicly available, the Excel used to have link for download which is now non-functional. A Python version of the code has been developed recently [115], but not made publicly accessible. This latest version has defined interfaces for interoperability and is portable across platforms (accessibility level 2).

The source code of the DynACof model is unconditionally available in a public online repository [116]. The model code is licensed under the GNU Public License (GPL) and can therefore be obtained, changed and applied and published without further approval of the developer. The model has therefore ensured longevity and can be used or adapted in future, reaching accessibility level 5. However, the DynACof model is, by design, a highly specialized model for the specific needs of coffee production and provides no defined interfaces for interoperability.

The EPIC model in its original form, including its source code, is freely available [117]. The modifications by Easterling [33] to the weather generator for simulating agroforestry systems, however, are not publicly available (accessibility level 0). The original EPIC code [118] has been developed and has been updated continuously. The EPIC implementation is in the form of a monolithic structure and is not designed for modularity and tightly coupled interoperability. EPIC is written in a widely used programming language (FORTRAN) and released under the GPL license in a repository (accessibility level 5), so it is possible to reuse parts of the source code in another context—either adapted or fully translated to another programming language. The portable code can be compiled for most operating systems.

WaNuLCAS is developed inside of the commercial modelling system STELLA by iseesystems.com. The project files are hosted by the World Agroforestry Center (ICRAF) [119]. The license allows free non-commercial use of the code but does not mention rights for reuse and changes—both conditions make the license incompatible with licenses approved by the Free Software Foundation (accessibility level 4). The dependency on third- party commercial software prohibits interoperability in a framework and modular use of sub-models.

Hi-sAFe's code is available from the projects homepage and is written in JAVA on top of the forest modelling platform Capsis [120] and integrates the generic crop growth model STICS [121], written in FORTRAN. Both foundation models are highly modular and well suited for model interoperability, as Hi-sAFe itself proves. Hi-sAFe can be obtained from the authors free of charge, albeit with very limited rights for the user to extend, change or distribute these changes (accessibility level 3), with the additional requirement that publications containing a Hi-sAFe application must include a co-author from the original development team. It is therefore not possible to include Hi-sAFe's code in a larger independent framework and hence, enhancements to cover more NCP relevant properties would require a formal authorisation and support from the development team.

The modifications to APSIM by Huth et al. [78] to model agroforestry systems, that include eucalyptus trees as shading and wind shelter elements for various annual crops, have recently been further developed and integrated into the APSIM modelling system [67]. The APSIM framework is highly modular in its design and for many processes contains alternative sub-models to choose from and runs on most operating systems. The source code is publicly available and model usage is free of charge for public research [79] (accessibility level 4). A commercial license can be obtained. The non-commercial license is free of charge and limited to three years and must be renewed regularly. New features can be contributed to APSIM, if the copyright of that development is given to the APSIM initiative (AI). Modifications, enhancements and related work cannot be published without the agreement of the AI. Coupling with code published under the GPL is not possible.

4.3. Do We Need to Start the Multi-Effect Framework from Scratch?

The road to multi-effect multi-crop frameworks to predict the ecological impacts of agroforestry practices at the field/landscape level starts with combining existing multi-crop growth models with existing tree growth models to allow consideration of relevant agroforestry-specific light, water and nutrient dynamics among interacting plant types. Only the detailed generic crop models Hi-sAFe, EPIC and APSIM are suitable to model practice gradients at the field scale and provide a basis for large scale meta-models. The model Hi-sAFe is built in this way and provides the widest range of tree/crop combinations. EPIC, WaNuLCAS and APSIM are the two other options for process-based generic models in this review. EPIC's approach to tree/crop interaction is rather simplistic [33] and lacking indirect effects of joint resource consumption of trees and ground crops; WaNuLCAS's design decision prevents its use in a wider framework [14].

The APSIM modelling framework covers most ecosystem properties that translate into NCPs. Smethurst et al. [67] introduced an agroforestry module for APSIM simulating shading and competition for nutrients and water, without the use of a proper tree growth model. Nutrients and water demand of trees are modelled as a sink term. Lateral fluxes of water and nutrients between tree and crop patches are not considered. The APSIM framework provides modularity, portability and interoperability as the source code of the respective modules is publicly accessible but restricted by the APSIM licence. As such, the APSIM approach to agroforestry modelling is promising, but lacks the freedom to independently develop modules within the framework.

5. Conclusions

Do agroforestry models currently include a *"broad and relevant set of ecosystem services at multiple spatial scales"* [19]? We have shown in Section 3 that current agroforestry models still focus predominantly on production and consider NCP regulation mainly as a means for biomass production and yield. That is to be expected, since other ecosystem services were not considered as target variables alongside production in agroforestry systems. Most agroforestry models have been developed with an even narrower scope, with specific combinations of a single tree species with a single crop species. Extending process models is a task for researchers as well as filling empirical gaps with virtual experiments. Such a new detailed modelling framework can be used for studies at the field scale and to derive simplified approaches, e.g., as meta-models for policy decision support and by NGOs for strategic decision support. Stakeholders with a focus on production, like farmers, and agricultural extension are already well equipped with existing, production focussed tools available for use at multiple scales.

With respect to nature's contributions to people, agroforestry models require further development and a broader scope. To include existing research work in further model enhancement, open-code policy is essential. To this end, stakeholders using models or model results to address knowledge gaps, offering advice and contributing to a broad range of NCPs, would also benefit from the structure highlighted in this study. Detailed, modular frameworks at the field level can help to improve simplified models and indicator systems. Currently, we see a lack of sufficiently modular, freely accessible and re-usable simulation frameworks (see Section 4), in which tree growth, crop growth, and components accounting for species competition, which could be further developed by other than the original research group. The ambition to produce a modelling framework that facilitates the simulation of a wide range of agroforestry's contributions to people is a great challenge, and it requires a community effort to advance in this field.

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Appendix A

Table A1. Agroforestry's ecosystem properties, assessed by the existing models. This table is the basis for Table 2. The symbols represent values for averaging. Legend: green: covered by model (1), amber: partly or overly simplistic coverage (0.5), red: ecosystem property not covered by model (0).

Group	Variable	Hi-sAFe	WaNuLCAS	SCUAF	APSIM	EPIC	SBELTS	WIMISA	COMP8	DynACof	Hypar	Yield-SAFE	ICBM/N	ESAT-A
Biodiversity	Plant species diversity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%
Biodiversity	Animal species diversity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Biodiversity	Landscape diversity	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Air quality	Aerosol mixing model	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Air quality	Wind profile	0%	0%	0%	100%	100%	100%	100%	0%	0%	0%	0%	0%	0%
Air quality	Wind erosion	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	100%
Climate	Plant C storage	100%	100%	50%	100%	100%	0%	0%	0%	100%	50%	50%	0%	0%
Climate	Soil C storage	0%	0%	0%	100%	100%	0%	0%	0%	0%	0%	100%	0%	50%
Climate	CO_2 emission	0%	0%	0%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Climate	N_2O emission	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Climate	CH_4 emission	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Climate	Albedo	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%
Climate	long-wave radiation	0%	0%	0%	100%	0%	0%	0%	0%	100%	0%	0%	0%	0%
Climate	ET (incl. moisture recycling)	100%	50%	0%	100%	100%	100%	100%	0%	100%	100%	0%	0%	0%
Climate	Surface roughness	0%	0%	0%	50%	50%	100%	50%	0%	0%	0%	0%	0%	0%
Climate	Cloud formation	0%	0%	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Water	Groundwater recharge	100%	100%	0%	100%	100%	100%	0%	100%	0%	100%	100%	0%	100%
Water	N leaching	100%	100%	0%	100%	100%	100%	0%	100%	0%	100%	100%	0%	100%
Water	P export to water bodies	100%	100%	0%	100%	0%	0%	0%	100%	0%	100%	100%	0%	100%
Water	Water supply to plants/Competition	100%	100%	100%	100%	100%	0%	100%	100%	100%	100%	100%	0%	0%
Water	N supply to plants/Competition	100%	100%	100%	100%	100%	0%	0%	100%	100%	100%	100%	0%	0%
Surface protection	Water erosion	0%	100%	100%	100%	100%	0%	0%	0%	0%	0%	100%	0%	100%
Surface protection	Surface friction	0%	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Surface protection	Vegetation cover	100%	100%	100%	100%	0%	0%	100%	0%	0%	100%	100%	100%	100%
Surface protection	Preferential flow path infiltration	0%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Productivity	Harvested crop yield	100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	100%	0%	0%
Productivity	Timber production	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%
Productivity	Wood production	100%	100%	100%	0%	0%	0%	0%	0%	100%	100%	0%	0%	0%
Productivity	Fruit production	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Productivity	Single crop	100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	100%	0%	0%
Productivity	Multiple crops	100%	100%	0%	100%	100%	0%	0%	0%	0%	0%	100%	0%	0%
Productivity	Specific trees	100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	100%	0%	0%
Productivity	Multiple trees	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%

Figure A1. The same content of Table A1, with different presentation effect.

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